

The determinants of CO₂ emissions of air transport passenger traffic: An analysis of Lombardy (Italy)

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ABSTRACT

We study the determinants of aviation CO₂ emissions by designing an econometric model applied to a panel data set covering all flights departing from Lombardy, Italy over the 1997–2011 period. We consider two dimensions of CO₂ emissions: total and per available seat kilometer. The latter is a measure of emission efficiency. We focus on different categories of determinants: technical progress; aircraft and network carrier management; policy/business decisions that may not be oriented to limiting CO₂, but may indirectly affect it by offsetting projected outcomes of policies adopted to reduce emissions (e.g., the EU Emission Trading Scheme (ETS) or the ICAO Carbon Offsetting and Reduction Scheme for International Aviation); and others. We find that although aircraft size increases total emissions, it reduces emissions per available seat kilometers (ASK), while the route distance increases total emissions and decreases emissions per ASK, implying that CO₂ is less of a problem for long-haul connections. Technical progress decreases CO₂ emissions per ASK with an estimated elasticity equal to -0.06% . Last, liberalization in the EU market has generated the development of low-cost carriers, which in turn have lowered CO₂ emission per ASK, that is, liberalization in Europe has brought the collateral effect of reducing the CO₂ externality per passenger.

1. Introduction

With an average growth of 5% annually (Vespermann and Wald, 2011), global aviation activities play a key role not only in industry performance and economic development, but also in climate change. Among other pollutants (i.e., NO_x, SO_x, H₂O, soot, PM₁₀, contrails and cirrus), the amount of carbon dioxide (CO₂) produced by commercial aviation is substantial. In 2005, CO₂ was estimated to be 1.6% of total anthropogenic radiative forcing (Lee et al., 2009).

According to the Air Transportation Action Group (ATAG)¹ the global aviation industry, counting over 3 billion air passengers, produced 705 million tons of CO₂ in 2013, accounting for 2% of the human-induced CO₂ emissions and 13% of total transportation-related emissions. According to the 2016 European Aviation Environmental Report by European Aviation Safety Agency (EASA), there were 80% more European flights in 2014 compared with the number of flights in 1990. This environmental impact has increased regardless of possible technology improvements: in 2014, there was +5% more aviation-

induced CO₂ with respect to the level in 2005, and +44–53% more CO₂ is estimated in 2035.

Politicians and regulators have agreed to limit CO₂ emissions in response to public pressure on the issue of climate change. For instance, the 2015 Paris agreement established a temperature increase limit to 1.5°C above pre-industrial levels.² In 1997, the Kyoto Protocol was signed, and the International Civil Aviation Organization (ICAO) was assigned to lead the establishment of global aviation CO₂ regulation. Reaction to this regulation varied among countries. New Zealand and Australia initiated domestic aviation emission trading in 2010 and 2012 respectively, while the EU introduced the Aviation Directive in 2012 on both intra-EU and extra-EU flights as an extension of its already implemented Emission Trading Scheme (ETS) in other sectors in 2005. Extra-EU flights were then waived after legal action had been brought against the directive by some airlines and the International Air Transport Association (IATA)—the so-called “stop the clock” decision that should have stayed enforced until 2016. However, to the best of our knowledge, the directive is still in force today.

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¹ ATAG is an independent coalition of organizations and companies of the aviation industry, formed in 1990.

² Paris Agreement, an agreement within the United Nations Framework Convention on Climate Change, is adopted by consensus on 12 December 2015.

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After several meetings, during its 39th assembly, the ICAO approved a global market-based measurement (GMBM) scheme, the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). This type of scheme will be enforced through different phases starting in 2020 (see [Scheelhaase et al., 2018](#), for a detailed discussion). CORSIA, which is different from the EU-ETS, will be applied to all flights, not only flights in the European Economic Area.

Despite the ongoing, time-consuming negotiation process to limit CO₂ aviation emissions and reaching a path of environmentally sustainable growth, little is still known about factors that affect the amount of CO₂ generated by this sector. For instance, [Chèze et al. \(2011a, 2011b\)](#) point out that air traffic management (ATM), incremental innovation in existing aircraft, and substantial innovation (i.e., new aircraft) are the main drivers for reducing aviation emissions, including CO₂. [Grampella et al. \(2017a\)](#) show that a younger aircraft can generate –1% of local emissions per year and –0.3% of global pollution. However, to the best of our knowledge, research on econometric evidence of the determinants of CO₂ aviation emissions remains lacking. Specifically, a measure of the average flight distance impact on CO₂ emissions could provide the fundamentals for designing an ETS that is based on flight distances rather than a general overall reduction in annual airlines CO₂ emissions (equal to 95% of the average historical aviation emissions during the 2004–2006 period). This per-flight CO₂ emissions regulation could provide incentives to airlines for better aircraft management on different routes. For instance, such regulations could provide incentives to operate an aircraft fitting current demands on specific routes and thus avoid using aircraft flights with low load factors on some routes. Thus, providing an econometric estimate of the sign and magnitude of some factors regarding CO₂ aviation emissions is the first goal of this paper.

Moreover, it is necessary to take into account that CO₂ emissions comprise only one dimension in the air transportation sector, as emissions interact with such factors as economic performance, political motives, and regulations on market entry, among others. All of these other components influence the possible outcomes of decisions adopted to limit emissions. For instance, although liberalization may boost CO₂ emissions by stimulating demand through lower fares, a company restructuring its network to recover profitability may lead to lower emissions through more efficient ATM. In this paper we aim to consider the impact of such non-emission specific decisions on the amount of CO₂ generated by aviation. This will provide, if proven, that these factors should be included in a cost-benefit analysis that also covers the environmental effects (direct and indirect) of a political or management decision.

To accomplish this, we exploit three circumstances: (1) the impact of regulation identified by the liberalization of the EU industry; (2) the impact of political decisions, given by a traffic transfer Act that swaps flights between two airports; and (3) the role of managerial decisions such as de-hubbing to reshape the flight network and to recover profitability.

We analyze these issues by exploring data on aviation activities and aviation-related CO₂ emissions in Italy. Specifically, we focus on Lombardy in Northern Italy.³ We design an econometric model to identify the impact of certain determinants of CO₂ aviation emissions and apply it to a new data set that spans from 1997 to 2011 and consists of all scheduled flights departing from Lombardy airports in January of each year. The per-flight CO₂ emissions are based on the aircraft model and the distance flown.

³ Lombardy is one of Europe's wealthiest regions and exceeded 10 million inhabitants in 2016. Other than the exceptional tourism volume, Lombardy has important commerce, banking, fashion and design sectors in Milan, as well as strong industries and agriculture in Bergamo. Lombardy is one of the four motors for Europe (with Baden-Württemberg (Germany), Catalonia (Spain), and Auvergne-Rhône-Alpes (France) identified by the European Commission.

The effect of non-environment decisions is provided by the estimated effect on CO₂ emissions of the entry (deregulation) of low-cost carriers (LCCs) when the national government decided in 1998 to impose an aircraft-movement cap to one airport (Linate). The decision was made to transfer flights to Malpensa in order to have a hub in Lombardy (a political reason). In addition, in 2008, at the apex of one of its recurrent financial crisis, Alitalia decided to reshape its network and concentrate flights at Rome Fiumicino in an attempt to recover profitability (a managerial decision).

Each of these factors may have affected CO₂ emissions in different ways. For instance, some LCCs could have generated new flights (increasing CO₂), changing the pattern of air traffic by possibly focusing on shorter routes (decreasing CO₂ per passenger), divert passengers from other CO₂-intensive transportation modes (e.g. cars, buses, trucks for freight), use younger aircraft and generate higher load factors than traditional carriers, and hence lower CO₂ emissions per passenger.⁴ Similar considerations could be developed for limiting Milan Malpensa (e.g., reshaping both the flight network and the aircraft management) and for Alitalia Malpensa's de-hubbing decision (LCCs may have replaced Alitalia flights with—if proven—connections using younger aircraft).

Our period of observation covers 15 years, starting in 1997 and ending in 2011. The beginning year allows us to consider the full impact of some exogenous decisions (e.g., the 1998 swap from Linate to Malpensa and the impact of liberalization that took place in the mid-2000s). The last year is limited to 2011 for data availability. Although we can look at the three-year period following the Malpensa de-hubbing to see the effects on CO₂ emissions, such a review does not allow us to consider both the impact of recent CO₂ regulations such as the EU ETS (begun in 2013) and of ICAO CORSIA (approved in 2016).

The paper is organized as follows. Section 2 describes the literature review. Section 3 discusses our empirical strategy by computing the per-flight CO₂ emissions and presents the econometric model. Section 4 describes the available data sets, the data mining process, and descriptive statistics in the econometric model variables. Section 5 presents our empirical results, while Section 6 concludes the paper and highlights some possible policy implications. The Appendix contains assumptions on aircraft models and a list of LCCs defined by the ICAO.

2. Literature review

Currently, two main streams of research on aviation externalities exist. The first stream focuses on the impact of aviation externalities (mainly emissions and noise) on airports' vicinity, while the second stream investigates the future impact of aviation emissions on climate change using *ad-hoc* algorithms.

Regarding the first stream, [Schipper \(2004\)](#) conducted a landing/take-off (LTO) cycle assessment and estimation on 1990 data. Vicinity environmental costs of European aviation were computed from noise, emissions, and accident risk, and then applied to a set of 36 European markets (routes) in a week in 1990. [Lu and Morrell \(2006\)](#) performed a similar study on four European airports and showed, after computing an aviation externality, that a large part of such externality (noise in this case) was omitted. [Morrell and Lu \(2007\)](#) compared hub-to-hub and hub-bypass networks and found that the latter generated fewer emissions than the former. [Lu \(2009\)](#) studied aviation emissions' charge effect on air transportation demand and provided some evidence that environmental surcharges could reduce passenger demand, especially in the case of LCCs, even if these carriers impose lower environmental costs to passengers. [Givoni and Rietveld \(2010\)](#) investigated narrow-body A320 and wide-body B747 in two routes (London-Amsterdam and Tokyo-Sapporo) and showed that higher aircraft size and lower frequency generates lower climate change costs but higher local pollution.

⁴ We are grateful to Martin Dresner for raising this point.

However, the latter does not offset the benefit of the former—i.e., high aircraft size produces lower overall (local plus global) emissions. Lu (2011) calculated the environmental (social) costs and social benefits at Taoyuan International Airport in Taiwan, providing evidence that even considering the aviation externalities, the benefits of having an airport are greater than the costs.

The papers belonging to this stream of research aim at the total environmental cost or the best solution to limit externalities. They provide solutions such as an optimum fleet mix, giving importance to load factors, or to adopting newer, cleaner technologies. Moreover, these papers usually only consider the LTO cycle and not the whole flight journey. When vicinity environmental cost is studied, LTO is the best approach, as aviation activity lower than 1-km altitude most affects a neighborhood.⁵ When studies explore the issue of different emissions and noise levels generated by various aircraft models and engine types, they adopt a simplifying assumption of using some categories rather than the specific aircraft/engine combination. An exception is Grampella et al. (2017b), who used certificate data for each aircraft-engine specification. They applied this approach to a data set on a national airport system (Italy) and found that aircraft size-total externality elasticity is +1.8%, aircraft movement elasticity is +1%, and aircraft age elasticity is +0.69%. Again, as they focused on airport vicinity effects, the LTO cycle emissions and noise were studied.

In this first stream of research, analyzing global emissions or CO₂ emissions in particular, was not emphasized. However, according to the IPCC⁶ (2007), “about 50% of a CO₂ increase will be removed from the atmosphere within 30 years, and a further 30% will be removed within a few centuries. The remaining 20% may stay in the atmosphere for many thousands of years.” Hence, this paper, by focusing on CO₂ emissions, is an attempt to fill this literature gap.

The second group of papers focuses on forecasting CO₂ emissions mainly through computing fuel efficiency improvement. Hence, the main difference in this second stream is not finding the determinants of emissions, but rather using some algorithms based on the current and projected technology status to compare future alternative scenarios. Macintosh and Wallace (2009) developed an emissions projection (algorithm) by projecting revenue tons kilometers (for aviation demand) and global aviation emission intensity. Four scenarios were created from 2005 to 2025 based on forecasts of traffic growth and projections of technical progress aimed at reducing emissions. The scenarios showed that the latter is unlikely to offset the increase in CO₂ due to traffic growth. Chèze et al. (2011a) forecasted the yearly growth of air traffic flows until 2025, then converted the information into quantities of jet fuel using a geographic zone-specific energy coefficient, which is the amount of jet fuel required to power a unit of transportation. They provided evidence of an annual reduction of 3% in CO₂ emissions through lower fuel consumption thanks to both technical progress and better ATM. Chèze et al. (2011b) extended these results in which forecasts of future CO₂ emissions between international and domestic flights were compared, with the latter generating more emissions than the former, mainly due to a different (less environmental friendly) fleet mix.

Clearly, the findings of the second stream of research papers strongly depended upon *ad-hoc* assumptions of future demand and performance. A certain year is studied and then different scenarios based on hypothetical numbers of annual growth and improvements are plugged in that predict the future. Although a base past year can be carefully investigated, and the trend can then be calibrated, radical

improvements or temporal events discriminating the base year or violating the trend cannot be netted by this method. Our paper is closer to the first stream of research, as we focus on finding some determinants of CO₂ emissions.

In addition to the two main research streams, there have been many contributions closer to our approach. Miyoshi and Mason (2009) proposed a bottom-up calculator for CO₂ emissions by route, stage length, aircraft type, number of seats on each aircraft, and the distance flown on each route. They used 2006 data for domestic air traffic and 2004 data for North Atlantic air traffic and provided a methodological reference for a part of our empirical research—namely, the computation of a specific aircraft CO₂ emissions during a specific route length. Pejovic et al. (2008) provided the same methodological base using samples from a day in 2004 to simulate the total annual CO₂ emissions. We follow these approaches, but use richer data and include several airports in a region.

Some recent papers have published empirical evidence on some determinants of CO₂ growth rates in aviation. Scotti and Volta (2015) found that European airlines grew 18.4% and 26.7% in terms of available seat kilometers (ASK) and revenue passenger kilometers (RPK) respectively from 2000 to 2010—i.e., airlines are carrying more people for a longer distance and earning more than before. They computed airline productivity in emission generation and identified the factors affecting it, providing evidence that load factor and a combined increase in stage length and aircraft size are determinants of increasing emission productivity, while fuel efficiency is a determinant only in the presence of a specific measure aimed at increasing CO₂ productivity. Brugnoli et al. (2015) examined CO₂ emissions in Europe and found that per-seat emissions were decreasing and suggested that the main factors leading to this result are airlines' effort to save on fuel costs, as well as the endogenous technical progress of the manufacturing industry. Kharina and Rutherford (2015) pointed out that the average fuel burn of new aircraft fell 45% from 1968 to 2014, and consequently CO₂ emissions fell. They also identified industry technical progress as the main determinant of this outcome.

However, even the recent contributions that are more related to our paper have not evaluated the direct impact of policies and management decisions not taken to reduce aviation environmental effects on total CO₂ emissions. This is possible in our paper, as we focus on airports in one region experiencing forces from different angles. As such, we consider the potential effect of business decisions made by Europe, Italy, and the aviation industry on Lombardy's aviation CO₂ emissions. This would allow for the control of such factors that may even offset the benefits that could come from, for instance, technical progress. Hence our paper is the first attempt, to the best of our knowledge, to establish the impact of decisions not intended to reduce CO₂ emissions on the amount of this externality generated by aviation. Thus, controlling for these factors, we aim to obtain better estimates of the influence of some determinants of CO₂ emissions—e.g., technical progress.

3. Empirical strategy

As mentioned in the introduction, our main goal is to estimate the signs and magnitude of some CO₂ emission determinants generated by aviation, and to assess how they are affected (or even counterbalanced) by some non-environmental measures taken by regulators, politicians, and industry managers.

As a first step in defining our empirical strategy to achieve such goals, we establish our research questions. First, we consider some determinants investigated by previous contributions (e.g., Scotti and Volta, 2015) that are typical of the aviation sector—such as the price of fuel—that may provide an incentive to reduce fuel consumption to save costs and therefore lead to more environmentally friendly aircraft/engine combinations. Hence, our first research hypothesis is as follows.

RH1. The price of fuel may be a negative determinant of aviation CO₂

⁵ The LTO cycle refers to aircraft activity in altitudes below 3000 feet (915 & #x202F; m). Emissions during LTOs are a concern when studying local air quality and health impacts.

⁶ The IPCC, Intergovernmental Panel on Climate Change, is a scientific body focusing on human-induced climate change, formed in 1988 in the United Nations.

emissions.

Similarly, the amount of CO₂ generated by a flight is strongly related to the route distance—i.e., the longer the stage length, the higher the CO₂. This argument is the basis of our second research hypothesis.

RH2. The route distance may be a positive determinant of CO₂ total emissions. However, we cannot make *ex-ante* predictions regarding the effect of distance on per-seat CO₂ emissions.

Moreover, the aircraft size has an impact on the thrust power and, in turn, the amount of CO₂ emissions. Hence we can investigate the issue below.

RH3. The average aircraft size may be a positive determinant of CO₂ total emissions. However, we are not able to make *ex-ante* predictions regarding the effect of size on per-seat CO₂ emissions.

Another typical determinant often considered in the air transportation literature is general technical industry progress (Grampella et al., 2017b). This is given by the aggregation of incremental innovations introduced in aircraft/engine combinations and in industry operations (e.g., better ATMs) that may generate an annual reduction in the amount of CO₂ emissions. Hence, we specify a trend variable capturing the impact of general technical progress.

RH4. : The technical industry progress is a negative determinant of both aviation CO₂ total emissions and per-seat emissions.

In addition to the abovementioned factors, we focus on some other determinants that may indirectly affect CO₂ and may offset the general benefits provided, for instance, by technical progress. The first determinant is related to aviation general regulation and in particular to the EU liberalization of air transportation. The latter has two main effects: (1) the entrance of LCCs and (2) the increase of flights (and routes).⁷ The distance flown is already captured by the increase in flights and routes. The entrance of LCCs may instead reduce CO₂ emissions because they use, for example, younger aircraft. Hence we have our further research hypothesis.

RH5. LCCs may be a negative determinant of both total and per-seat CO₂ aviation emissions.

The second exogenous indirect determinant is given by Alitalia's de-hubbing from Malpensa that occurred in April 2008 with the full effects starting in 2009.⁸ This decision left several empty slots at Malpensa that were used by other airlines in the following years. The situation then created an entry opportunity, as well as the eventual establishment of a network in Malpensa, with possibly new and different-sized aircraft. Hence, the de-hubbing may have had the effect of reducing CO₂ emissions for flight limitations in the short run, which may have counteracted the entry effect over time. Moreover, the new airline networks may have had a positive impact on per-seat CO₂ emissions, for operating younger aircrafts and better ATM. This leads to the research hypothesis below.

RH6. Alitalia's de-hubbing from Malpensa in 2008 may have an effect on total and per-seat CO₂ emissions.

Lastly, the Italian national government's decision to impose a cap on flights at Milan Linate to help develop Milan Malpensa, which took place in 1998 (with full effects during the following year), may have generated a restructuring of the airline networks at both airports.⁹ If

Alitalia concentrated flights in Malpensa in an attempt to build a second hub (Rome Fiumicino is Alitalia's first hub), as shown by Redondi (2013), this may have increased the flight frequency and, in turn, the CO₂ emissions.¹⁰ Moreover, such a concentration may have increased the aircraft size per movement, which could have reduced per-seat CO₂ emissions. Regarding the other airlines, they may have restructured their networks in both airports, thus affecting total and per-seat CO₂ emissions. Hence, no *a priori* impact could be identified. Our last research hypothesis is therefore the following.

RH7. The flight cap imposed on Milan Linate 1998 is a determinant of both total and per-seat CO₂ emissions.

In order to investigate these research questions, we first measured the CO₂ emissions generated by the sample of airports affected by the abovementioned exogenous decisions. Second, we designed an econometric model to provide some statistical evidence of the estimated coefficients of the possible determinants.

The airports included in our analysis are the four located in Lombardy, the region affected by the Italian government's decision, as well as the de-hubbing by Alitalia's. The four airports in Lombardy include Milan Malpensa (MXP), Bergamo Orio al Serio (BGY), Milan Linate (LIN), and Brescia Montichiari (VBS). We consider a 15-year time period, from 1997 to 2011. At the beginning of this period, Malpensa was the second-largest Italian airport with about 20 million passengers annually and the first that carried freight. Linate was the third-largest Italian airport with about 9 million passengers. Bergamo ranked sixteenth with 1.2 million passengers annually, but was third in terms of freight. Brescia was in the twenty-seventh position, with about 150,000 passengers annually, and no freight. At the end of the period, Malpensa ranked second in Italy, with about 19 million passengers annually (a reduction compared with the beginning figure, even though the sector has expanded in Italy), and first in terms of freight, with strong growth (+50% compared to the beginning of the year). Bergamo has had exponential growth; in 2011, there were 8.5 million passengers annually. The airport was ranked fifth in Italy, and third in terms of cargo. In 2011, Linate had about 9 million passengers annually, as in the initial year (1997). Brescia had almost no passengers in 2011 but significantly in terms of freight, passing from zero movement in year 1997 to about 40 thousand annual tons in 2011, ranking sixth in Italy. Currently, although Malpensa is still ranked second, in 2017, the airport grew to 22 million passengers annually and by far the first in terms of freight. Bergamo is currently the third Italian airport with 12.3 million passengers and third in freight. Linate ranks fifth with 9.5 million passengers, and Brescia still has very few passengers but ranks sixth in freight.¹¹

We measured the amount of CO₂ emissions generated by these four airports during the observed period and then estimated the impact of some determinants. We now show how we measure aviation CO₂ emissions and subsequently present our econometric model.

(footnote continued)

Malpensa in the observed period. As such, a traffic distribution rule (TDR) was put on Linate when a new terminal in Malpensa was completed in 1998. The TDR, called Burlando Act (enacted by the Italian Minister of Transport and Navigation in 1998), fixed the Linate quota to 34% of its capacity, meaning that around 8.5 million of its 14.5 million passengers had to move from Linate to Malpensa. Moreover, in 2000, with the Bersani Act (enacted by the succeeding Minister), Linate was officially capped by a further TDR that limited the service to European markets (e.g., only three and two daily returns to London Heathrow and Frankfurt, respectively).

¹⁰ Redondi (2013) has explained how airlines fought back the TDR by multiple carrier codes or slot leases. Linate missed chance of 10% of growth as a consequence of TDR.

¹¹ Data was collected from Assaeroporti, an Italian airport association of the 36 companies managing the 38 airports in Italy, which was founded in 1967 and is affiliated with the Airport Council International.

⁷ This implies generally considering the effect of Ryanair entry into the Bergamo airport in 2003, of easyJet's entry into the Malpensa airport in 2004 and of other LCCs such as Wizz Air and Flybe making smaller entries into various airports (mainly Bergamo) in the observed period.

⁸ Seventy-six percent of departing flights were canceled and 17 daily intercontinental flights shrank to 3 non-daily intercontinental flights.

⁹ This was based on the blueprint of a second Alitalia national hub in

3.1. Measurement of aviation CO₂ emissions

We considered departing flights from Lombardy in order to avoid unnecessary definition challenges of other perspectives—that is, entering flights, residency of passengers, airlines' base, or kerosene sales. In addition, only direct flights were considered; in cases of connecting flight, only the first leg leaving Lombardy was included.

We analyzed two flight phases: (1) the LTO cycle; and (2) the climb, cruise and descent cycle (CCD). These are divided, as fuel is burned in different patterns and has different types of environmental impact. In particular, during the LTO cycle, fuel flow can change with an engine's rated output in power settings of corresponding activities such as taxing, take-off, and climb out.

We considered an aircraft's total emissions on a particular journey. With the aid of the small emitters tool (SET) by Eurocontrol,¹² we obtained the estimated total fuel consumption of a certain aircraft model given the flight distance. SET takes the actual fuel consumption data of each flight under the EU ETS initiative and then runs separate linear regressions of each aircraft model, defining two parameters: the intercept (at zero distance) and the slope (kg of fuel per nautical miles flown). The overall fuel consumption is then translated into CO₂ according to the aircraft's engine type. In this study, we used the SET version 5.05 dated 2015.12.26. When some aircraft models in the sample could not be found in the SET, assumptions were made (See Appendix I for conversion table.).

We computed two CO₂ emissions indices: (1) the total amount and (2) the emission efficiency given by the amount of CO₂ generated by the available seat kilometers (ASK). As the total CO₂ emissions of a route is principally proportional to distance and frequency, by employing the second index, long-distance or high-frequency routes were not discriminated. Utilizing available seats in the second index formation further screened out the effect of varying aircraft sizes.

3.2. The econometric model

Our aim is to identify the determinants of total and per-ASK CO₂ emissions generated by the four Lombardy airports during the 1997–2011 period. Hence, we developed an econometric model to estimate the elasticity of some determinants on CO₂ emissions and to provide empirical evidence of the possible effects of decisions that may indirectly affect such emissions. Therefore, we used a log-linear model in which some determinants were expressed in logarithms and others as dummy variables. Airport dummy variables were also created as control variables. In this log-linear model, the percentage impact on a dependent variable when a dummy variable switches from 0 to 1 could be computed by applying the following expression: $100(e^{\delta} - 1)$, where δ is the coefficient for the dummy variable. In the presence of a continuous variable as a regressor, given that the dependent variable is logged, its elasticity is given by β —i.e., the estimated coefficient of the logarithmic independent variable.

Our observation is given by the origin-destination (OD), the route provided by an airline in year t . The triplet origin-destination-airline (or the pair route-airline) is our “id” variable, with the label i . Hence we have a panel data set composed by $i \times t$, $i = 1, 2, \dots$, and t triplets origin-destination-airline during the period $t = 1997, \dots, 2011$. Four hundred and thirty-five routes and 197 different airlines were observed in the period data set; however, since not all routes operated every year, we had only 1082 route-airline pairs. Hence we generated an unbalanced panel data set composed of 4164

observations.

We designed two econometric panel data models and then estimated the models with random effects (RE) that are presented below (respectively, the first equation estimates the determinants of total CO₂ emissions while the second concerns the factors affecting per-seat-kilometer CO₂ emissions):

$$\begin{aligned} \log CO2_{it} = & \alpha + \beta_1 \times \log FUEL_t + \beta_2 \times \log KM_{it} + \beta_3 \times \log SIZE_{it} \\ & + \beta_4 \times TIME_t + \delta_1 \times DEHUB_t + \delta_2 \times 1998_t + \delta_3 \times LCC_i \\ & + \delta_4 \times EU_i + \sum_{j=1}^3 \gamma_j \times D_airport_{ij} + \epsilon_{it} \end{aligned} \quad (1)$$

$$\begin{aligned} \log CO2ASK_{it} = & \alpha + \beta_1 \times \log FUEL_t + \beta_2 \times \log KM_{it} + \beta_3 \times \log SIZE_{it} \\ & + \beta_4 \times TIME_t + \delta_1 \times DEHUB_t + \delta_2 \times 1998_t + \delta_3 \times LCC_i \\ & + \delta_4 \times EU_i + \sum_{i=1}^3 \gamma_i \times airport_i + \epsilon_{it} \end{aligned} \quad (2)$$

where i is the pair route-airline, t is the year, and j is the index regarding the three departing airports in Lombardy (Malpensa is the base airport). The model is estimated to account for possible heteroskedasticity—i.e., the estimate coefficients have robust standard errors. The effect of technology progress on CO₂ emissions is captured by the variable $TIME$ given by each year in the dataset. Equation (2) has a dependent variable given by an index of emission efficiency—that is, the amount of CO₂ per-seat per kilometer of flight ($CO2ASK$). Furthermore, as our aim is also to study the determinants of one-year variations in total CO₂ emissions and per-seat-kilometer CO₂ emissions, we estimated a panel data model with a one-year difference in time-varying variables and random effects given by the two following equations:

$$\begin{aligned} \log\left(\frac{CO2_{it}}{CO2_{it-1}}\right) = & \alpha + \beta_1 \times \log\left(\frac{FUEL_t}{FUEL_{t-1}}\right) + \beta_2 \times \log\left(\frac{KM_{it}}{KM_{it-1}}\right) \\ & + \beta_3 \times \log\left(\frac{SIZE_{it}}{SIZE_{it-1}}\right) + \delta_1 \times (DEBUG_t - DEBUG_{t-1}) \\ & + \delta_2 \times (1998_t - 1998_{t-1}) + v_{it} \end{aligned} \quad (3)$$

where Eq. (3) is related to variations in total CO₂, while Eq. (4) is for per-seat-kilometer CO₂,

$$\begin{aligned} \log\left(\frac{CO2ASK_{it}}{CO2ASK_{it-1}}\right) = & \alpha + \beta_1 \times \log\left(\frac{FUEL_t}{FUEL_{t-1}}\right) + \beta_2 \times \log\left(\frac{KM_{it}}{KM_{it-1}}\right) \\ & + \beta_3 \times \log\left(\frac{SIZE_{it}}{SIZE_{it-1}}\right) + \delta_1 \times (DEBUG_t - DEBUG_{t-1}) \\ & + \delta_2 \times ((1998_t - 1998_{t-1})) + v_{it} \end{aligned} \quad (4)$$

Table 1 illustrates the variable names and description.

The model presented in Eqs. (1)–(4) is applied to a data set described in the section below.

4. Data

We built a data set that included all Lombardy passenger flights from 1997 to 2011, all scheduled flights in January of each year departing from Lombard airports: Malpensa (MXP), Linate (LIN), Bergamo (BGY), and Brescia (VBS). The source of these data is the Official Airline Guide (OAG) database. The airports have different destination (airports), distances, carriers, frequencies, aircraft models, and available seats. CO₂ emissions are then estimated by feeding the aircraft model and distance traveled into SET, the emission calculation tool. We collected 4197 observations and some descriptive statistics on the observed flights, and their CO₂ emissions are shown in Table 2. The average, annual amount of total CO₂ generated by a route-airline pair is about 800 thousand kilograms, while the per-seat-kilometers is only 97 g +

Table 3 presents descriptive statistics of the variables that may indirectly affect emissions and the share of flights departing from the four

¹² SET was approved by the European Commission via the Commission Regulation (EU) No.606/2010 and is used by small emitters in fulfillment of their obligations pursuant to Article 14(3) of the Directive 2003/87/EC (the EU ETS Directive) and Part 4 of Annex XIV to Decision 2007/589/EC (monitoring and reporting guidance).

Table 1
Description of variables.

Variable	Description
CO2	Total amount of CO ₂ emissions in kg of a particular route-airline <i>i</i> pair in year <i>t</i>
CO2ASK	Grams of CO ₂ produced by flying one available seat per 1 km in pair <i>i</i> and year <i>t</i>
FUEL	Fuel price in January of year each in US cents
KM	Distance of a route in km (variable since a route can involve flying to different airports at same destination)
SIZE	Average aircraft size in the route-airline pair <i>i</i> in year <i>t</i>
TIME	Year index starting from 0 and up to 15
DEHUB	De-hubbing effect, starting at 2009, i.e. 1997–2008 as 0; and 2009 onward as 1
1998	Traffic distribution from LIN to MXP, i.e. 1997–98 as 0; and 1999 onward as 1
LCC	A set of LCC airlines defined by ICAO definition (see Appendix II) as 1
EU	Dummy variable = 1 if destination is in Europe
AIRPORT	Dummy variable of departing airports

Table 2
Descriptive statistics of observed routes.

Variable	Mean	St. Dev.	Min	Max
CO2 (kg)	821,386.4	1,203,953	2236	9,607,554
CO2ASK (g)	97.3	32.4	54.9	443.5
FUEL (\$)	1.4	0.7	0.3	2.6
KM	6146.9	8554.9	64	133,800
SEAT	2016.2	2470.7	97	11,195
SIZE	154.6	67.78	19	546
ASK	9,104,834	1.30E+07	17,296	9.58E+07

Table 3
Descriptive statistics of independent variables.

Variable	Mean	St. Dev.	Min	Max
DEHUB	0.34	0.47	0	1
1998	0.96	0.19	0	1
LCC	0.21	0.41	0	1
EU	0.77	0.42	0	1
Bergamo	0.14	0.34	0	1
Brescia	0.01	0.09	0	1
Milan Linate	0.24	0.43	0	1
Milan Malpensa	0.62	0.49	0	1

airports. It is interesting to note that the average share of LCC flights is 21% in our sample while the share of those with destinations in the EU is 77%. Observations regarding the Malpensa airport comprise the majority (62%), while those related to Brescia are only a small percentage (1%).

Concerning the destination composition, also seen in Fig. 1, the total

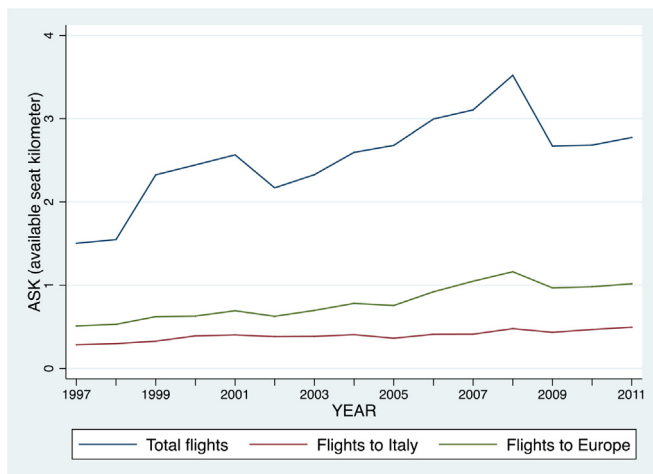


Fig. 1. Annual ASK (billion) departing in January from Lombardy by destination.

amount of EU ASK¹³ varies from about 0.5 billion in 1997 to about 1 billion in 2011, while the total amount of ASK ranges from about 1.5 billion to about 2.8. Last total Italy ASK¹⁴ increases from about 0.3 billion to about 0.5 billion. The ASK is growing in all levels with respect to the 1997 level.

Fig. 2 shows the effects of the traffic transfer Act and of Alitalia's de-hubbing on the level of ASK in Linate and Malpensa. The left-hand graph displays the impact of the Italian government's decision to transfer the traffic from Milan Linate to Milan Malpensa in 1998. It is evident that there is a big ASK reduction in Linate and a corresponding increase in Malpensa. The right-hand graph presents the impact of Alitalia de-hubbing from Malpensa, which involved a huge reduction in the ASK and no corresponding increased effect on Linate.

Fig. 3 reveals the share of aviation CO₂ emissions among the four airports in the data set. We show the total CO₂ emissions in regards to only departing flights in January of each year. The emission levels would be scaled up if every month in a year was considered, or if the incoming flight was also measured. The traffic distribution—that is, the steered traffic from Linate to Malpensa—is obvious since Linate has a sharp decrease of CO₂ emissions in 1999, while Malpensa has a sharp increase. Moreover, it is evident that the effect of Alitalia de-hubbing from Malpensa in 2009, with a strong reduction in total CO₂ emissions, is not counteracted by any increase in the other four Lombardy airports. Lastly, the development of LCCs in the Bergamo airport (mainly due to Ryanair) generates a continuous increase in total CO₂ emissions.

As we are interested in the technology progress reflected by the emission efficiency variations given by CO₂ per ASK (i.e., grams of CO₂ produced by one available seat per kilometer), the latter is computed for each flight. We can see the diverse LCC performances (red line in Fig. 4) compared with all airlines (blue lines) and the index number of flights departing from the four airports (Fig. 5). It is interesting to notice that LCCs have a lower CO₂ per ASK than traditional airlines. Moreover, Bergamo had a significant improvement in 2003 when LCCs began proliferating there. All airports or airlines have a decreasing trend of CO₂ per ASK, which could be a signal of environmentally friendly technical progress; however, the total CO₂, which we encountered before, has an increasing trend.

Finally, we present the indicator trends based on the 1997 value in Fig. 6. From this graph, we confirm the questionable relation of total CO₂ and CO₂ per ASK: the total CO₂ is unevenly increasing while CO₂ per ASK is steadily decreasing. ASK is confirmed to be correlated to CO₂ but we question if the fuel price is significantly impacting the CO₂ per ASK.

The 30 most important airlines in our data set are listed in Table 4. They are in ascending order of CO₂ per ASK. The share of the total of

¹³ We refer to the EU ASK as the available seat kilometers to an EU destination; i.e., an intra-EU flight.

¹⁴ IT ASK refers to the seat kilometers of a destination in Italy—i.e., a domestic flight.

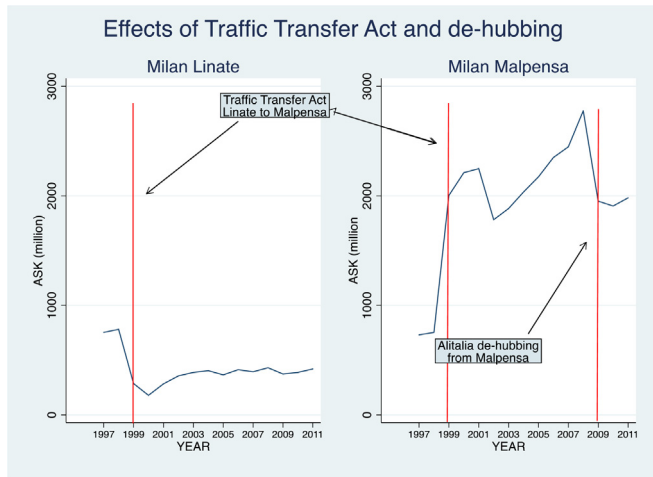


Fig. 2. Annual January departure ASK (million) from Lombardy by airport.

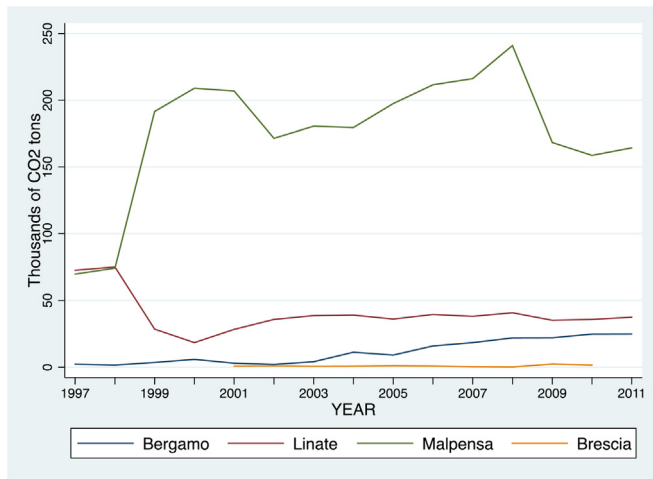


Fig. 3. Annual January departure CO₂ by airports in Lombardy.

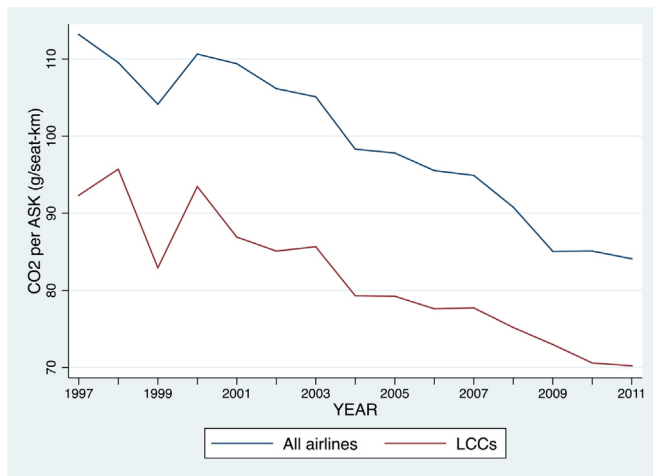


Fig. 4. Annual January departure CO₂ per ASK by LCCs.

these 30 airlines on the grand total of 197 airlines is reported, representing at least 80% of all dimensions including total CO₂, total frequency (movement), total km (distance) and total ASK. Total ASK is also a proxy of air transportation supply. The average seat and average km by movement could be interpreted as the median aircraft size and median route distance, respectively, of each airline.

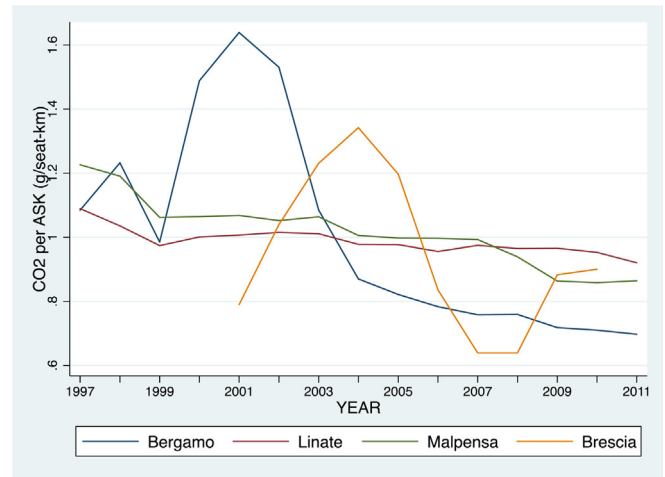


Fig. 5. Annual January departure CO₂ per ASK by airport.

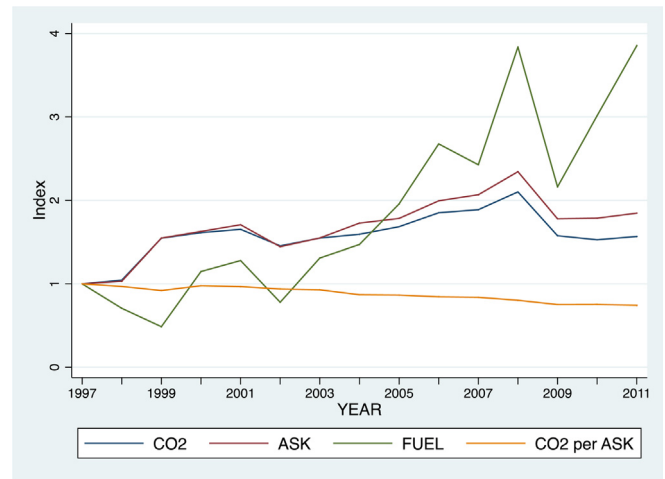


Fig. 6. Trend of annual January departure indicators based on the year 1997.

5. Results

In this section we present empirical evidence regarding the seven previous research questions. We first show the estimated coefficients regarding the model for total CO₂ emissions (Eq. (1)), under two specifications: (1) with a dummy for all LCCs; and (2) with a dummy regarding only Ryanair and easyJet. The latter captures the impact on CO₂ emissions of the two most important LCCs in Europe with a strong presence in Lombardy; moreover, these two LCCs also tend to have younger aircraft.

The regressions outcome is shown in Table 5, with four models of different settings. The dependent variable of the first two models is the total amount of CO₂, while that of the latter two models is CO₂ per ASK. Regarding the independent variables, most of them are statistically significant, reflecting their impact on Lombardy aviation CO₂ emissions in an airline-specific route dimension by the corresponding coefficients' sign and magnitude. LCC is tested by two different definitions: (i) a list of LCCs by ICAO and (ii) only Ryanair and easyJet. In the (ii) case, the magnitude of impact is always strengthened.

When all LCCs are considered, as expected, distance (KM) and size (SIZE) have a positive impact on total CO₂ aviation emissions. The estimated elasticity is respectively +0.63% and +0.41%. Unexpectedly, the fuel price (FUEL) is also a positive determinant of total CO₂ emissions: the estimated elasticity is +0.11%. On the contrary, we do not find any evidence of technical progress effect on total CO₂. The exogenous policy and managerial variables also have no effects; however, if

Table 4
Listing of important airlines in Lombardy.

CODE	CARRIER NAME	Total CO ₂ (kt)	Total Frequency	Total SEAT (thousand)	Total KM	Total ASK (million)	SEAT (mean)	KM (mean)	CO ₂ per ASK (g/ seat-km)
FR	Ryanair	103.86	9063	1709.27	8,441,413	1591.68	188.60	931.41	65.25
GJ	Eurofly	47.46	1078	215.34	2,711,191	643.06	199.76	2515.02	73.80
L4	Lauda Air	44.79	325	84.73	2,291,080	598.20	260.70	7049.48	74.88
U2	easyjet	72.95	6860	1069.81	6,185,361	964.38	155.95	901.66	75.64
LM	Livingston	59.73	462	119.66	2,915,541	763.14	259.00	6310.69	78.28
IB	Iberia	39.76	2924	489.92	2,935,138	499.86	167.55	1003.81	79.53
TP	TAP Portugal	20.74	1224	157.70	1,993,140	258.93	128.84	1628.38	80.10
PE	Air Europe	40.66	1749	266.70	2,447,032	500.77	152.48	1399.10	81.19
EK	Emirates	37.95	353	110.81	1,509,276	464.46	313.91	4275.57	81.71
BV	Blue Panorama Airlines	33.82	447	84.3	1,986,810	409.28	188.59	4444.77	82.64
VA	Volare Airlines	18.71	1207	201.99	1,213,669	219.82	167.35	1005.53	85.10
VE	CAI Second	30.75	1886	302.42	2,014,763	360.67	160.35	1068.27	85.27
DL	Delta Air Lines	79.55	620	131.57	4,259,775	904.45	212.20	6870.60	87.95
BA	British Airways	57.61	4794	657.95	4,815,786	650.72	137.24	1004.54	88.53
KL	KLM	20.53	2193	276.97	1,769,673	223.54	126.30	806.96	91.84
IG	Meridiana	58.78	4932	776.69	3,755,284	635.78	157.48	761.41	92.46
AZ	Alitalia	1483.26	76,657	10,053.92	87,571,292	15,786.57	131.15	1142.38	93.96
XM	CAI First	29.64	2549	368.86	2,139,463	311.15	144.71	839.33	95.25
AF	Air France	37.34	5370	654.29	2,952,033	384.38	121.84	549.73	97.14
CO	Continental Airlines	54.89	398	86.79	2,559,836	558.21	218.07	6431.75	98.33
SK	SAS Scandinavian Airlines	29.36	1809	233.46	2,350,695	298.15	129.05	1299.44	98.49
AP	Air One	105.28	13,205	1631.50	8,501,515	1060.45	123.55	643.81	99.28
SQ	Singapore Airlines	40.57	260	72.28	1,442,418	400.99	278.00	5547.76	101.18
JL	Japan Airlines International	90.47	325	117.77	2,453,119	884.92	362.36	7548.06	102.23
RG	Varig	67.90	382	96.623	2,628,354	662.19	252.94	6880.51	102.53
LH	Lufthansa Airlines	65.64	10,479	1053.77	5,977,403	596.71	100.56	570.42	110.01
OS	Austrian Airlines	12.40	1741	167.42	1,125,979	108.23	96.16	646.74	114.53
SN	Brussels Airlines	16.68	1981	201.39	1,338,995	136.38	101.66	675.92	122.34
G7	Gandalf Airlines	6.70	2124	75.71	1,204,055	43.51	35.64	566.88	153.92
LX	Swiss	6.10	1894	171.56	392,066	35.08	90.58	207.00	173.90
Sum (30)		2813.88 (82.26%)	159,291 (83.68%)	21,641.14 (84.53%)	173,882,155 (80.38%)	30,955.68 (82%)	135.86	1091.60	90.90
Total (197)		3420.92	190356	25600.396	216326034	37921.81	134.49	1136.43	90.21

Table 5
Regression results for total CO₂ aviation emissions.

Variables	Dependent variable: log of CO ₂					
	Estimated coefficient	S.E.	P-value	Estimated coefficient	S.E.	P-value
log FUEL	0.109***	(0.036)	0.002	0.109***	(0.036)	0.002
log KM	0.628***	(0.063)	0.000	0.621***	(0.063)	0.000
log SIZE	0.406***	(0.066)	0.000	0.390***	(0.066)	0.000
TIME	−0.015	(0.010)	0.123	−0.016	(0.010)	0.108
DEHUB	−0.010	(0.043)	0.810	−0.013	(0.043)	0.762
1998	−0.007	(0.057)	0.900	−0.005	(0.057)	0.928
LCC	0.005	(0.070)	0.946			
EU	0.279**	(0.124)	0.024	0.233*	(0.123)	0.058
Linate	0.188***	(0.072)	0.009	0.206***	(0.072)	0.004
Bergamo	−0.436***	(0.083)	0.000	−0.505***	(0.077)	0.000
Brescia	−0.089	(0.229)	0.696	−0.153	(0.236)	0.517
LCC_R_E				0.317***	(0.081)	0.000
Constant	12.520***	(0.513)	0.000	12.672***	(0.509)	0.000
Observations	4164			4164		
R ²	0.34			0.34		

Robust standard errors in parentheses.

Legend: *** P-value < 0.01, ** P-value < 0.05, * P-value < 0.10.

the destination is in a EU member country, the total CO₂ is higher (the estimated elasticity is about +0.32%). Bergamo makes much less total CO₂ than Malpensa, which might be explained by the fact that almost all Bergamo flights are operated by LCCs, and this may explain why the

variable LCC has no significance. Linate makes more CO₂ emissions than Malpensa, possibly due to older aircraft (Alitalia operated the Milan Linate-Rome Fiumicino routes that used a lot of old MD-80/81/82 for many years). Interestingly, when Ryanair and easyJet are included in the regression, the estimated effect is positive—i.e., they increase the total CO₂ emissions. In the case of Ryanair, the result may be explained by the negative coefficient for the Bergamo airport. Malpensa also makes less CO₂ than Linate, which may capture part of the possible negative effect from easyJet. This finding is confirmed by the results of a regression (not shown) that does not include the airport dummies; in this case, the LCC dummy is negative and significant.

Table 6 presents the results concerning emission efficiency—i.e., the CO₂ per ASK that is related to Eq. (2). The fuel price is not a determinant of CO₂ per ASK. Interestingly, the route distance and aircraft size are negative determinants of emissions (in)efficiency, as they both generate lower CO₂ per ASK. The estimated elasticities are, respectively, −0.14% and −0.28%. Moreover, there is a positive impact of technical progress on emission efficiency: the estimated coefficient for TIME is equal to −0.01, corresponding to a −0.06% annual improvement—a lower CO₂ emission per ASK. De-hubbing and the transfer traffic decision have no effect, while LCCs are producing less CO₂ per ASK than traditional carriers. These findings are confirmed and slightly higher in magnitude when we consider only Ryanair and easyJet. Flying to a EU destination yields a lower CO₂ per ASK, which may also be due to liberalization and airports charging pollution surcharges. Linate and Bergamo are more efficient than Malpensa.

We have also analyzed the impact of some possible determinants of the one-year changes in the amount of CO₂ generated per route-airline

Table 6
Regression results for total CO₂ per ASK aviation emissions.

Variables	Dependent variable: log of CO ₂ per ASK					
	Estimated coefficient	S.E.	P-value	Estimated coefficient	S.E.	P-value
<i>log FUEL</i>	−0.001	(0.009)	0.918	−0.000	(0.009)	0.977
<i>log KM</i>	−0.140***	(0.016)	0.000	−0.142***	(0.016)	0.000
<i>log SIZE</i>	−0.282***	(0.020)	0.000	−0.283***	(0.020)	0.000
<i>TIME</i>	−0.006***	(0.002)	0.004	−0.007***	(0.002)	0.002
<i>DEHUB</i>	−0.010	(0.010)	0.318	−0.007	(0.010)	0.478
<i>1998</i>	0.007	(0.015)	0.656	0.007	(0.015)	0.643
<i>LCC</i>	−0.129***	(0.014)	0.000			
<i>EU</i>	−0.220***	(0.032)	0.000	−0.223***	(0.032)	0.000
<i>Linate</i>	−0.048***	(0.014)	0.001	−0.046***	(0.014)	0.001
<i>Bergamo</i>	−0.086***	(0.015)	0.000	−0.097***	(0.015)	0.000
<i>Brescia</i>	−0.018	(0.048)	0.703	−0.005	(0.047)	0.919
<i>LCC_R_E</i>				−0.168***	(0.014)	0.000
<i>Constant</i>	7.189***	(0.148)	0.000	7.201***	(0.149)	0.000
Observations	4164			4164		
R ²	0.53			0.53		

Robust standard errors in parentheses.

Legend: *** P -value < 0.01, ** P -value < 0.05, * P -value < 0.10.

Table 7
Regression Results for one-year variation in total and per-seat CO₂ emissions.

Variables	Dep. var.: log of CO ₂			Dep. var.: log of CO ₂ x ASK		
	Est. Coef.	S.E.	P-value	Est. Coef.	S.E.	P-value
<i>log d.FUEL</i>	0.080**	(0.032)	0.012	0.0004	(0.009)	0.965
<i>log d.KM</i>	5.326	(7.807)	0.495	−0.164	(1.533)	0.915
<i>log d.SIZE</i>	0.400***	(0.075)	0.000	−0.342***	(0.038)	0.000
<i>d.DEHUB</i>	−0.012	(0.046)	0.800	0.0001	(0.009)	0.992
<i>d.1998</i>	0.079	(0.050)	0.111	0.015	(0.015)	0.325
<i>Constant</i>	−0.024*	(0.012)	0.056	−0.006***	(0.002)	0.007
Observations	2930			2930		
R ²	0.03			0.20		

Robust standard errors in parentheses.

Legend: *** P -value < 0.01, ** P -value < 0.05, * P -value < 0.10.

pair and on the CO₂ per ASK using the model presented in Eqs. (3) and (4). The results are shown in Table 7. The first three columns have the logarithm of the total CO₂ generated as the dependent variable (i.e., the columns refer to Eq. (3)), while the last three columns give the results of regressing Eq. (4), with the logarithm of the CO₂ generated per ASK as the dependent variable. Both the dependent and the independent variables are the one-year difference, denoted as “d.”

One identified determinant of one-year changes on total CO₂ is the one-year variation in aircraft size. If the latter increases we observe an increase in the variation of total CO₂ from one year to the following year. The estimated coefficient of the *d.SIZE* logarithm is equal to +0.40 and is statistically significant. The other determinant is given by the one-year variation in fuel price: the estimated coefficient is statistically significant and equal to +0.08. One-year variations in the route distance, the impact of Alitalia de-hubbing, as well as the 1998 Traffic Transfer Act from Linate to Malpensa have no effect on the total CO₂ one-year difference.

Table 7 shows that the only identified determinant of one-year changes in CO₂ per ASK is the one-year variation in aircraft size. The estimated coefficient is −0.34, which implies that a one-year increase in aircraft size yields a reduction in the one-year CO₂ generated for passengers (using seat kilometers as a proxy average). This is an interesting result since it demonstrates that a marginal (i.e., in the following two years) increase in aircraft size can produce a marginal

decrease in the amount of CO₂ generated per passenger. This finding could signal a possible lower per-passenger impact of aviation on the environment if we could progressively augment the per-route aircraft size, keeping all other variables fixed (the sign and significance is the same if we also include a one-year variation in the total ASK operated on the route, after taking into account the total movements on that route).

Hence, to sum up our insights regarding the research questions, we can state the following. First, fuel price increases the total CO₂, differently from what we had expected. This suggests that airlines are not pushing efficiency in fuel consumption, which has the secondary effect of increasing emissions and might be explained by market power—that is, airlines may be transferring higher fuel costs to consumers. We did not find any effect on CO₂ per ASK and on one-year variations. Second, the route distance increases total emissions, and decreases emission per ASK, thus we have higher efficiency with a longer flight distance, implying that CO₂ is less of a problem for long-haul connections. There is no impact of distance on one-year variations. Third, although aircraft size increases total emissions, it reduces emissions per ASK, as well as one-year variations; therefore, it is a driver of emission efficiency. Fourth, technical progress does not impact total emissions, but it does decrease CO₂ emissions per ASK in that the estimated elasticity is −0.06%. Fifth, although LCCs have lower CO₂ emissions per ASK, as liberalization in Europe has brought a collateral effect of reducing CO₂ externality per passenger, LCCs also contribute to higher total emissions, probably due to their higher activity in the EU. Sixth, Alitalia de-hubbing and the national government traffic transfer act from Linate to Malpensa did not have any effect any on the investigated dimensions of CO₂ emissions, including one-year differences. This implies that managerial and government decisions made for reasons not connected with the environment did not generate an impact on CO₂, which is different from what was expected. In both cases, the airlines’ network restructuring could generate an effect, but this has not been identified.

6. Conclusion

This study is an attempt to fill a gap in the existing literature regarding the possible determinants of CO₂ emissions generated by the commercial air transportation sector. Previous contributions (e.g., Chèze et al., 2011a; Grampella et al., 2017b) have identified that technical progress is a factor limiting emissions and we estimate an annual improvement in the range of −1% and −0.3%. However, other peculiar factors of the air transportation sector may influence CO₂ emissions—for instance, route distance and aircraft size. Furthermore, different institutions (ICAO, EU, and so forth) are involved in a lengthy process of establishing a policy limiting aviation emissions, with the EU ETS and the ICAO CORSIA framework as two examples. However, these efforts interact with other forces such as economic and business performance, political issues, and regulation on market entry. The latter factor may affect possible outcomes of decisions adopted to limit emissions. For instance, market liberalization may boost CO₂ emissions by stimulating demand through lower fares. Hence, in this contribution we analyzed the determinants of CO₂ aviation emissions that include different components: technical progress, traffic management airline decisions, and policies/business choices not oriented to the environment, but that can indirectly affect the level of emissions.

We studied emissions according to two dimensions: (1) the total CO₂ generated on a specific route by a specific airline, and (2) the CO₂ per ASK on the same unit of observation. While the first dimension provide insight into the determinants of global amounts of CO₂, the second may point out a relative measure of CO₂ per passenger—i.e., the environmental efficiency of air transportation.

In order to identify the determinants of CO₂ aviation emissions we designed an econometric model for panel data and applied it to a data set concerning all the flights departing from Lombardy, Italy, over the 1997–2011 period. The amount of CO₂ generated was computed by

taking into account the aircraft model chosen by the airline operating on that route.

Our main results are as follows. First, the price of fuel is a positive determinant of total CO₂ emissions (RH1) but has no effect on per seat emissions. Airlines seem not to react to price variations in setting their schedule, maybe because the rebate the changes on higher ticket fares (Scotti and Volta, 2018). Second, as expected route distance increases total CO₂ emissions and decreases emissions per ASK (RH2). The latter outcome implies that there is higher emission efficiency for long-haul connections. Third, aircraft size increases total emissions, but reduces emissions per ASK (RH3); therefore, it is a second driver of emission efficiency. These two factors indicate that airline fleet management may be a sustainable growth path for commercial aviation. Fourth, there is a positive effect of general technical progress on per seat CO₂ emissions but not on total ones (RH4). Hence, differently from previous studies, once that we focus on the route-airline pairing we find that technical progress is not impacting total emissions, but it is decreasing CO₂ emissions per ASK. However, the estimated elasticity is lower than previous figures (−0.06%) and, above all, much lower than the estimated elasticities regarding aircraft management (the route elasticity is −0.14%, the aircraft size elasticity is −0.28%). Fifth, we provided mixed evidence regarding the indirect impact of policy/business decisions (not oriented toward CO₂) on emissions. On the one hand, the EU market liberalization has an impact on CO₂, and this may offset the outcome of other policies (e.g., the EU ETS or the ICAO CORSIA) adopted to limit pollution. In the observed period (1997–2011) liberalization has brought the entry and the development of LCCs into the EU, and we find that they have high total emissions, but lower CO₂ emission per ASK (RH5). The latter result implies that although liberalization has brought the collateral effect of reducing the CO₂ externality per passenger, it has also contributed to higher total emissions, probably due to higher LCC activity in the EU. On the other hand, we find that Alitalia de-hubbing from Malpensa in 2008 (RH6) and the national government Traffic Transfer Act from Linate to Malpensa in 1998 do not affect either total or per ASK CO₂ emissions (RH7). In both

cases the airlines' network restructuring could have generated an effect, but this has not been identified.

From the abovementioned insights we can draw some interesting policy implications. First, aviation CO₂ emissions could be reduced, or emission efficiency could be increased through airline adoption of better aircraft and network management. Aircraft size can reduce CO₂, thus environmental policy should provide incentives for increasing aircraft size on different routes when demand allows for it, for instance, by reshaping the EU ETS according to this dimension. A higher tax may induce airlines to better aircraft management when possible, perhaps with less frequency and higher load factors. Second, it is necessary to provide an incentive to renovate aircraft fleets, since general technical progress is a determinant of aviation emission efficiency. Last, LCCs also increase emission efficiency, a further important consequence. This is because LCCs may generate new flights (increasing CO₂), divert passengers from other CO₂-intensive transportation modes (e.g., cars, buses, trucks for freights), use younger aircraft and generate higher load factors than traditional carriers, hence achieving a overall lower CO₂ emissions per passenger.

Restricted by the availability of data and resources, there are some limitations and drawbacks of this study. First and foremost is the underestimation of CO₂ emissions through the following examples: when an equivalent aircraft model (with a lower CO₂ emission value) is used for a badly defined aircraft model in our data set; when theoretical distance is used instead of actual distance flown (which is possible if each flight is monitored); when operation usage of fuel on the ground is neglected (although this might be responsible for only a tiny part of fuel consumption). A dedicated airport study should also take these factors into account. Second, in this paper CO₂ emissions are not an actual measurement of each flight in this, but a proxy. We compute CO₂ emissions based on a regression of certain aircraft model records, which is, by its nature, estimated. Third, no comparisons of different aircraft categories were made in this study. Engines and airframes characterize small/medium-large aircraft and thus fuel consumption. These topics are left for future research.

Appendix I Aircraft Model Conversion

OAG name	OAG code	SET code	OAG name	OAG code	SET code
Airbus A300 Passenger	AB3	A30B	BAe 146–300 Passenger	143	B463
Airbus A300B2/B4/C4	AB4	A30B	BAe Jetstream 32	J32	JS32
Airbus A300B4/A300C4/A300F4	ABX	A30B	Beechcraft 1900D Airliner	BEH	B190
Airbus A310 Freighter	31F	A310	Boeing (douglas) DC10 (Freighter)	D1F	DC10
Airbus A310 Passenger	310	A310	Boeing (douglas) MD-11 (Freighter)	M1F	MD11
Airbus A310-300 Freighter	31Y	A310	Boeing (douglas) MD-11 Mixed Config	M1M	MD11
Airbus A310-300 Passenger	313	A310	Boeing (douglas) MD-11 Passenger	M11	MD11
Airbus A318	318	A318	Boeing (douglas) MD-80	M80	MD81
Airbus A318/319/320/321	32S	A318	Boeing (douglas) MD-81	M81	MD81
Airbus A319	319	A319	Boeing (douglas) MD-82	M82	MD82
Airbus A320	320	A320	Boeing (douglas) MD-83	M83	MD83
Airbus A321	321	A321	Boeing (douglas) MD-87	M87	MD87
Airbus A330	330	A330	Boeing (douglas) MD-88	M88	MD88
Airbus A330-200	332	A332	Boeing (douglas) MD-90	M90	MD90
Airbus A330-200 Freighter	33X	A332	Boeing 717-200	717	B712
Airbus A330-300	333	A333	Boeing 727 (Freighter)	72F	B721
Airbus A340	340	A340	Boeing 727 Advanced all Series (Pax)	72S	B721
Airbus A340-200	342	A342	Boeing 727-200	722	B722
Airbus A340-300	343	A343	Boeing 727-200 Advanced	72A	B722
Airbus A340-500	345	A345	Boeing 737 (Freighter)	73F	B732
Airbus A340-600	346	A346	Boeing 737 Advanced all Series	73S	B732
ATR 42-500	AT5	AT45	Boeing 737 Passenger	737	B732
ATR 72	AT7	AT72	Boeing 737-200 (Mixed Configuration)	73M	B732
ATR42/ATR72	ATR	AT43	Boeing 737-200/200C/200QC (Pax)	732	B732
Avro RJ100	AR1	RJ1H	Boeing 737-200/200C Advanced (Pax)	73A	B732
Avro RJ70	AR7	RJ70	Boeing 737-300 (Freighter)	73Y	B733
Avro RJ70/rj85/rj100	ARJ	RJ70	Boeing 737-300 (winglets) Passenger	73C	B733
Avro RJ85	AR8	RJ85	Boeing 737-300 Passenger	733	B733
BAe (BAC/ROMBAC) 1–11 500	B15	BA11	Boeing 737-400 Passenger	734	B734
BAe (BAC) 1-11	B11	BA11	Boeing 737-500 Passenger	735	B735
BAe 146 Passenger	146	B461	Boeing 737-600 Passenger	736	B736

BAe 146-100	141	B461	Boeing 737-700 (winglets) Passenger	73W	B737
BAe 146-200 Passenger	142	B462	Boeing 737-700 Passenger	73G	B737
Boeing 737-800 (winglets) Passenger	73H	B738	Embraer 120 Brasilia	EM2	E120
Boeing 737-800 Passenger	738	B738	Embraer 170	E70	E170
Boeing 747 (Freighter)	74F	B741	Embraer 170/195	EMJ	E170
Boeing 747 all Series (Mixed Conf)	74M	B74D	Embraer 175	E75	E170
Boeing 747 all Series (Passenger)	747	B74D	Embraer 190	E90	E190
Boeing 747-200 (Freighter)	74X	B742	Embraer 195	E95	E190
Boeing 747-200B/200C (Passenger)	742	B742	Embraer RJ 135/140/145	ERJ	E135
Boeing 747-300/747-100/200 Sud (Pax)	743	B741	Embraer RJ135	ER3	E135
Boeing 747-400 (Mixed Configuration)	74E	B744	Embraer RJ145	ER4	E145
Boeing 747-400 (Passenger)	744	B744	Embraer RJ145	EM4	E145
Boeing 747-400F (Freighter)	74Y	B744	Fairchild Dornier 328-100	D38	J328
Boeing 757 (Passenger)	757	B752	Fairchild Dornier 328jet	FRJ	J328
Boeing 757-200 (winglets) Passenger	75W	B752	Fairchild Metroliner	SWM	SW4
Boeing 757-200 Passenger	752	B752	Fokker 100	100	F28
Boeing 757-200 PF (Freighter)	75F	B752	Fokker 50	F50	F50
Boeing 767 Freighter	76F	B762	Fokker 70	F70	F70
Boeing 767 Passenger	767	B762	Fokker F27 Friendship/Fairchild F27	F27	F27
Boeing 767-200 Passenger	762	B762	Fokker F28 Fellowship all Series	F28	F28
Boeing 767-300 Passenger	763	B763	Ilyushin IL-86	ILW	IL86
Boeing 767-400 Passenger	764	B764	Ilyushin IL-96-300	IL9	IL96
Boeing 777 Passenger	777	B772	McD-Douglas DC10 all Series (Pax)	D10	DC10
Boeing 777-200 Passenger	772	B772	McD-Douglas DC9 10/20 Series	DC9	DC91
Boeing 777-300 Passenger	773	B773	McD-Douglas DC9 30/40/50	D9S	DC93
Boeing 777-300 ER Passenger	77W	B773	McD-Douglas DC9-20	D92	DC92
Canadair Regional Jet	CRJ	CRJ1	McD-Douglas DC9-30 (Passenger)	D93	DC93
Canadair Regional Jet 100	CR1	CRJ1	McD-Douglas DC9-40	D94	DC93
Canadair Regional Jet 200	CR2	CRJ2	McD-Douglas DC9-50	D95	DC95
Canadair Regional Jet 700	CR7	CRJ7	Saab 2000	S20	SB20
Canadair Regional Jet 900	CR9	CRJ9	Saab 340	SF3	SF34
De Havilland DHC-8 Dash 8	DH8	DH8A	Tupolev TU134	TU3	T134
De Havilland DHC-8 Dash 8-400 Dash 8q	DH4	DH8D	Tupolev TU154	TU5	T154
De Havilland DHC-8-300 Dash 8/8q	DH3	DH8C	Yakovlev Yak-40	YK4	YK40

Appendix II. List of LCC by ICAO Definition

This is an extraction of LCC present in Lombardy in the observation period from the original document published by ICAO on their web site <http://www.icao.int/sustainability/Documents/LCC-List.pdf>.

Name of LCC	IATA Code	Registered in Lombardy
Air Arabia Maroc	3O	2010
Air Europe	PE	1999
Atlas Blue	8A	2007
Belle Air Europe	L9	2011
Belle Air	LZ	2007
Blue Air	OB	2008
Blue Panorama	BV	2011
Blue1	KF	2008
BMI Baby	WW	2003
Buzz	UK1	2001
Centralwings	CO	2006
Clickair	XG	2008
Condor Flugdienst	DE	2000
easyJet	U2	2004
Flybe	BE	2008
Germanwings	4U	2003
GO	GO	1999
ItAli Airlines	9X	2007
Jet2.com	LS	2004
Jet4you	8J	2008
MyAir	8I	2006
Niki	HG	2009
Norwegian Air Shuttle	DY	2011
Ocean Air	VC	2006
Ocean Air	7VC	2006
Pegasus Airlines	H9	2011
Ryanair	FR	2001
Sky Europe Airlines	NE	2003
SkyEurope Hungary	5P	2004
Sterling	NB	2003
Transavia.com	HV	2002
TUI Fly	X3	2008
Virgin Express	BQ	1997
Virgin Express	TV	1997
Vueling	VY	2005

Wind Jet
Wizz Air

IV
W6

2004
2005

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